International Report: Stormwater management

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Abstract An international survey of urban stormwater management (SWM) practice was conducted for IWA and produced contributions from 18 countries. The survey information was further expanded by a review of recent literature and summarised in this international report on SWM. The main findings of the survey include clear indications of a widespread interest in stormwater management and of the acceptance of a holistic approach to SWM promoting sustainable urban drainage systems (SUDS). Specific implications of this philosophy include emphasis on source controls in SWM, transition from traditional "hard" infrastructures (drain pipes) to green infrastructures, needs for infrastructure maintenance and rehabilitation, formation of stormwater agencies (within larger integrated water agencies) with participation of both public and private sectors, and sustainable funding through drainage fees rather than general taxes. Further progress in this field requires targeted research and development, knowledge sharing, and above all, a high level of public participation in planning, implementing and operating stormwater management systems.

Keywords Best management practices (BMPs); drainage infrastructures; financing; public participation; source controls; stormwater management (SWM); sustainable urban drainage systems (SUDS); urban stormwater runoff

Introduction

Discharges of urban stormwater may cause numerous adverse effects on urban areas (e.g. flooding) and on receiving waters, including flooding, erosion, sedimentation, temperature rise and species succession, dissolved oxygen depletion, nutrient enrichment and eutrophication, toxicity, reduced biodiversity, and the associated impacts on beneficial water uses (Marsalek, 1998). Such impacts were exacerbated by the traditional drainage systems and end-of-pipe solutions, which proved to be expensive and inefficient (Chocat *et al.*, 2001a). Increased concerns about such impacts led to the introduction of stormwater management, which represents a system of control and treatment strategies designed to mitigate such impacts either fully or partly. SWM measures, which are also referred to as best management practices (BMPs), are often implemented in the form of treatment trains representing a sequence of BMPs. Stormwater management has been practised in leading countries for more than 30 years, and it can be considered as a relatively mature issue, for which much information (and field experience) is available and should be of interest to others in a knowledge sharing process (Ellis, 1995). Typically, such information is available in conference proceedings (e.g. the proceedings of triennial Urban Drainage conferences, or NOVATECH conferences) and grey literature, of which availability is rather limited. Consequently, the International Water Association (IWA) decided to address the stormwater management issue by soliciting national reports on this subject, and a synthesis of their findings in the form of this International Report (IR). Thus, the purpose of this IR is to provide an international overview of the state of the art of stormwater management, with respect to technologies, policies, practices, influencing factors and trends, economics and financing, and research and development. As such, this report should be of interest to urban planners, water managers, municipal engineers, designers, and other stakeholders, including the public and citizen groups.

Terminology

Stormwater management is practised in many countries and this contributes to a diversity of terminology in this field. This situation is well recognised by the leading professional group in this field, The Joint Committee on Urban Drainage (formed under the auspices of IAHR and IWA), which is currently preparing an international glossary of urban drainage. For ease of communications in the preparation of national reports, definitions of selected technical terms used in SWM were distributed with the call for those reports and some of them are reproduced in Table 1.

Overview and limitations

Report scope

From the onset of this assignment, the authors recognised that the information produced by the survey of SWM practices would be limited by the number of contributions received, varying levels of comprehensiveness of the information supplied, and the “snapshot” nature of this survey. Consequently, the authors expanded the survey findings with information from other sources, including their own research and experience, literature surveys and discussions with colleagues. The scope of the IR was limited to stormwater management in separate storm sewer systems and reducing stormwater inflow to combined sewers. This limitation is in agreement with the terminology in Table 1. Thus, the issues of

Table 1 Terminology used in preparation of the international report

Term	Description
Best management practice (BMP)	A structural or non-structural measure employed in stormwater management for stormwater quantity and/or quality control.
Combined sewer	A sewer conveying stormwater as well as domestic, commercial, industrial and related wastewaters.
Combined sewer overflow (CSO)	Flow escaping from combined sewers, when their design capacity is exceeded (usually during wet weather).
Filter strip	A BMP serving for stormwater infiltration and treatment by the passage of sheet flow over dense turf providing biofiltration.
Infiltration	The downward and/or lateral movement of surface water into soils.
Storm sewer	A sewer conveying surface runoff (stormwater) only in separate sewer systems.
Stormwater (also storm water)	The water running off urban surfaces, as a consequence of rainfall over urban catchments. It may be conveyed through BMP facilities and separate storm sewers.
Stormwater detention	Temporary storage of stormwater in a storage facility, resulting in redistribution of flows and changes in stormwater quality.
Stormwater infiltration facility	A stormwater management facility designed to infiltrate stormwater into the ground (in the form of soakaway pits, infiltration trenches, wells, and basins).
Stormwater management	A process employing various non-structural and structural measures to control stormwater runoff with respect to its quantity and quality.
Stormwater management pond	A reservoir, with or without permanent water storage, used to store stormwater, reduce outflow peaks and enhance stormwater quality by physical, chemical and biological processes.
Stormwater retention	Storage of stormwater in a facility (or part of a facility) without any outflow.
Stormwater swale	A grassed earth channel used to intercept stormwater runoff and direct it to stormwater management facilities or conveyance elements. Swales retard flow, enhance stormwater infiltration, and provide stormwater treatment by biofiltration through grass.

combined sewer overflows with respect to their characterisation, control and impacts on receiving waters are considered to be outside of the IR scope and are not addressed here.

However, an important point must be made – while the focus on stormwater management only is acceptable and useful for addressing the management of surface runoff, this approach does not address the whole issue of wet weather pollution, which comprises stormwater discharges, sanitary sewer overflows, combined sewer overflows (CSOs) and wastewater treatment plant bypasses and/or reduced effectiveness in wet weather (Field *et al.*, 1998). This much broader, global issue is particularly important in countries with predominant combined sewer systems and perhaps should be addressed in one of the future international reports. In this broader approach, stormwater management would still retain some importance as a source control measure (Chocat, 2001; Schmitt, 2001), but many other practices involving flow storage and treatment, and system operation in real time would represent key measures for the abatement of wet-weather pollution.

Stormwater management overview

SWM is designed to mitigate the adverse impacts of urbanisation and its effects clearly extend beyond just the stormwater issues, by influencing many other important issues of urban waters, including flood protection, water supply management and protection, groundwater quality, wastewater management, and receiving water quality (Fujita, 1998). Consequently, SWM affects large urban populations and attracts the interest of the public. Because of this special nature, the SWM extends beyond just remedial technologies (as may be the case with some point sources) by combining technology, environmental policies and public participation. This special SWM characteristic has been confirmed by all the national SWM reports received.

SWM was considered as an important environmental issue in all the countries surveyed, regardless of their level of development (developing countries, Central and East European countries in transition, and developed countries), climate (annual precipitation ranging from 500 to more than 2,500 mm/yr), prevailing types of sewerage (ranging from 100% separate to 95% combined systems), and sewer system ownership and operation (typically public and private partnerships). However, there were large differences in the level of development of SWM in individual countries, ranging from a theoretical knowledge (awareness) of SWM concepts to widespread applications required under the current legislations (Chocat, 2001; Davis, 2001; Malmquist and Bennerstedt, 2001; Markowitz, 2001; Schmitt, 2001; Zabkova *et al.*, 2001). Large variations in the adoption of SWM practices were observed not only among countries, but also within individual countries, where some regions or individual cities may clearly lead (e.g. Barcelona in Spain; Lucino, 2001). These large differences in SWM uptake and practice indicate ample opportunities for technology transfer and knowledge sharing in this field.

There are large differences in SWM acceptance and implementation in new vs. old developments. While SWM is commonly practised in new developments and in the redevelopment of older areas, its retrofit in older developments with functional infrastructures is relatively rare. These differences are caused by the economic and feasibility conditions; in new developments, SWM is a part of the initial urban planning, and, therefore, space allowances are made for SWM structures and the associated costs are passed on to the house buyers. Complete urban redevelopment also allows substantial changes in the infrastructure layout and benefits of redevelopment projects (e.g. choice locations and government subsidies) support adoption of technically advanced approaches (Andersen and Schilling, 2001).

SWM practice is usually driven by national laws, which may deal with the protection of water quality in general or specific impacts of urban development on the environment. In member countries of the European Union (EU), as well as in the countries aspiring to join the EU, national environmental policies, including those addressing urban stormwater, are driven by the European policies and standards promulgated by the EU. Consequently, in this region, there will be a great deal of uniformity attained with respect to environmental legislation. However, outside of the EU, large variations in SWM objectives were noted in the 18 respondent countries. Such objectives ranged from runoff quantity control (Mok, 2001) to very broad objectives encompassing the protection and sustainability of receiving waters ecosystems, in support of their beneficial uses by society.

SWM is applied through specific measures, which are arranged in certain sequences (called treatment trains). Various terminologies were developed for such measures, including Best Management Practices (BMPs) in the USA, Alternative Techniques (AT) in France, or more recently, Sustainable Urban Drainage Systems (SUDS) in the UK (McKissock *et al.*, 2001). Such terms do not always refer to identical concepts and very often reflect a specific historical and cultural approach (Neittzke, 1999). All three expressions, BMPs, ATs and SUDS, are used extensively in the literature, but contain certain ambiguity with respect to the adjectives “best”, “alternative” and “sustainable”. In this report, for simplicity, the term BMPs is used for individual or grouped SWM measures and SUDS for the entire drainage systems.

BMPs (and SUDS) represent man-made complex environmental systems (e.g. constructed wetlands), whose performance may be difficult to quantify and sustain without proper support and maintenance. Furthermore, BMPs are management measures, which are expected to produce environmental benefits, but without strict performance targets (defined, e.g. for sewage treatment plants) and full understanding of their long-term operation (e.g. long-term sustainability) and benefits (e.g. improvements in biodiversity). BMPs represent dynamic environmental systems that evolve over time and their performance may change. Examples of changes in BMP parameters include vegetation growth, species distribution and maturity; reduction of storage volumes/flow areas due to sediment deposition; clogging of the BMP pervious layers; storage of contaminated sediments susceptible to contaminant release; transfer of contaminants from sediment to the biota, etc. Thus, BMPs also cause “secondary” impacts on the environment, which are not always well understood, or fully considered in the initial design. For sustainability of BMPs and mitigation of secondary impacts, maintenance is of paramount importance, and includes both short-term corrective measures as well as the long-term preventative maintenance including rehabilitation of BMP structures (MOEE, 1994; Bardin *et al.*, 2001a; Bertrand-Krajewski *et al.*, 2000).

Sustainability of BMPs (or of entire drainage systems, in SUDS) implies some equilibrium among the three sets of demands – those placed by the needs of environmental protection, economic needs, and the needs of the society. So far, most of our attention has focused on environmental needs, which are generally described by the mitigation of urbanisation impacts on the environment (e.g. attenuation of increased flows, sediment exports, and chemical and bacteria fluxes). Very little is known about the economic and social aspects of SUDS systems, which should facilitate a full development of urban water resources to meet the needs of the society.

Many competent textbooks and manuals exist for BMPs (e.g. Schueler, 1987; Azzout *et al.*, 1994; MOEE, 1994; Geiger and Dreiseitl, 1995; ASCE, 1998). In fact, while the design of individual measures is well covered in the literature, the difficult part is to select the best combination of measures, which would meet the project objectives. Such objectives may be given in terms which are different from those used to describe the detailed BMP performance (Barraud *et al.*, 1999). For example, the objective of the project may be to achieve a certain biodiversity (return of certain species, or maintenance of certain fish or benthic communities), but the BMP performance is typically described by removal of solids and chemicals from the treated runoff. The designer must be able to overcome these difficulties.

Stormwater management is applied at four levels referred to as: Policies and source controls, Site best management practices (BMPs) providing stormwater control and treatment, Community BMPs providing stormwater control and treatment, and Watershed-level measures. Brief descriptions of individual measures follow, recognising that the total number of BMPs is constantly growing by introductions of variations or combinations of the basic measures.

Policies and source controls

These non-structural measures are generally highly cost effective and for that reason are considered in all stormwater management plans. Many policies and measures fit into this category, including public awareness/education/participation; urban development planning; management of the material use, exposure and disposal controls; spill prevention and cleanup; prevention/elimination of illegal dumping and illicit connections; and street and stormwater facilities maintenance (ASCE, 1998). Public awareness, education and empowerment are essential for planning, design and acceptance of new stormwater facilities. Awareness and education are implemented through public meetings, open houses, tours of facilities, and visual displays at stormwater management sites. In this process, concerned citizen/environmentalist groups are formed which then actively engage in environmental projects, including environmental school projects, organised cleanups and publicity campaigns.

There is an ongoing debate about the relationship between technical and social issues with respect to water management, and specifically urban drainage (Geldof, 2001). It appears that the older school of thought of relying purely on technology to find solutions to water problems facing the society is losing its dominant position. At the same time, there are also concerns that solving water management problems (e.g. non-point source pollution, excessive water demands) by public education and behavioural changes only, is unrealistic. Perhaps the future solutions lie somewhere in between, in relying on technology where effective control can and must be exerted (e.g. potable water quality) and on social science approaches in non-structural measures dealing with source controls and changes in public and corporate attitudes and behaviours (Geldof, 2001). Some of the leading efforts in support of the latter approach are those adopted by the New South Wales Government Urban Stormwater Program (Smith, 2001) and the UNESCO initiative to develop a virtual, open university which would strive to develop a new common culture of water.

Urban development resource planning attempts to minimise the problems resulting from urbanisation. In this approach, new planning variables include population density and minimisation of runoff from new developments by minimising the catchment imperviousness and the associated impacts. Typical measures include progressive zoning ordinances and buffers for streams and wetlands. This approach requires a close co-operation between planners and drainage designers from the early stage of land development. Delayed involvement of water management designers leads to less than optimal results, with water management measures retrofitted into the preconceived plans (Bacon, 1997).

Material use, exposure and disposal controls strive to minimise the opportunity for contact between rainfall/runoff and various chemicals. This is generally achieved through good housekeeping, including phasing out the use of harmful chemicals (e.g. applications of herbicides in public parks), proper storage of chemicals that could pollute runoff (e.g. road salts), and ensuring a proper disposal of any left-over chemicals or materials. Spill prevention is practised to minimise the risk of spills during the outdoor handling and transport of chemicals. Besides instituting good practices for chemical handling, measures for spill containment (berms, enclosures, and separators) need to be developed. Illegal dumping and illicit connections need to be prevented or eliminated through public education (e.g. the yellow fish signs on sewer inlet grates), ordinances and their enforcement with penalties. This group of measures includes the management of both liquid and solid waste, including yard trash. Illicit connections should also be prevented by enforcement of ordinances and all other sources than runoff should be disconnected from storm sewers.

Finally, the drainage system performance needs to be sustained by street, storm sewer and BMP maintenance. Examples of maintenance procedures include street sweeping, catch basin cleaning, road and bridge maintenance, and specific maintenance measures recommended for individual BMPs (MOEE, 1994). While the value of maintenance operations for water quality improvement is generally recognised, such benefits and cost effectiveness are not clear in the case of street sweeping. Street sweeping improves the aesthetics of urban areas by removing debris and litter from streets. However, to achieve significant environmental benefits, it has to be done very frequently (to prevent pollutant wash-off by rain) and with the equipment capable of collecting fine particles carrying adsorbed pollutants. Typically, municipal departments, whose mandate may not include runoff pollution control, direct street sweeping operations. Sweeping operations designed to control runoff pollution would require a special operation regime and would be very costly. Balades and Petitnicolas (2001) noted that in a comparison of various BMPs, street sweeping was not among the most cost-effective measures for capturing and removing stormwater pollutants.

Lot-level source controls

These controls represent minor measures implemented at the lot-level in the form of mostly source controls. Such measures include enhanced rooftop detention, flow restrictions at catch basins to enhance local storage/detention, reduced lot grading to slow down runoff flow and enhance infiltration, redirecting roof leader discharges to ponding areas or soakaway pits, sump pumping of foundation drains (MOEE, 1994), and stormwater harvesting and reuse for sub-potable water supply. The most common stormwater reuse is for watering parks and gardens, but other uses were also examined or implemented (industrial process water supply, car washing, and, after thorough treatment, drinking water supply) (Fewkes, 1999). Stormwater harvesting is particularly common in the case of roof runoff (Appan, 1999; Herrman and Schmida, 1999). The feasibility of such options is usually controlled by economic considerations (Mikkelsen *et al.*, 1999).

Biofiltration by grass filters and swales. These measures reduce runoff volume by infiltration and enhance runoff quality by such processes as settling, filtration, adsorption and biouptake. Vegetated filter strips are feasible in low density developments with small contributing areas with diffuse runoff, suitable soils (good sorption), and lower groundwater tables. Good designs maintain shallow flow depths (50–100 mm), minimum filter lengths (> 20 m), and low slopes (1–5%). Swales are shallow grassed channels functioning in a similar way as vegetated biofilters. Good design features include the minimum bottom widths (> 0.75 m), mild slopes (< 1%), small contributing areas (< 2 ha), and adequate lengths (> 60 m). Swales are best suited for small areas with permeable soils and low groundwater tables (Schueler, 1987).

Infiltration facilities. These BMPs serve to reduce the volume and rate of runoff, reduce pollutant transport and recharge groundwater. Various forms of infiltration have been practised in almost all European countries for many years and still exist in spite of strong competition from conventional sewer networks for more than 100 years. Currently, there is a global tendency to develop or re-develop stormwater infiltration facilities. In some countries, like Switzerland, for example, infiltration of "unpolluted" wastewater (including stormwater) is mandatory. Other countries like Germany, Sweden or Denmark encourage the use of BMPs, and indirectly infiltration, through local or municipal incentive measures (Chocat *et al.*, 2001b; Schmitt, 2001).

Infiltration facilities are designed in various forms, including wells (pits), trenches, basins, and perforated pipes and drainage structures (catch basins, inlets, and manholes), often equipped with some pre-treatment measures, under-drains and bypasses (Schueler, 1987; MOEE, 1994; Urbonas, 1994). All these structures reduce the volume of runoff by allowing some stormwater to infiltrate into the ground. Since the infiltrating runoff contains pollutants, infiltration facilities also control pollution export from drained areas. The use of infiltration is generally feasible in smaller residential areas with low risk of groundwater contamination, soils with good percolation rates, and deeper groundwater or bedrock. Layouts of infiltration facilities must avoid septic tanks and building foundations. In general, infiltration structures can be very cost effective. However, there are concerns about their applications – potential contamination of groundwater and uncertain life expectancy.

To reduce runoff from pavements, permeable and porous pavements were developed. In permeable pavement structures (PPS), the pavement contains macro-openings through which stormwater infiltrates into the road structure and possibly the surrounding soils (Bond *et al.*, 1999). Porous pavements utilise porous surficial materials (e.g. porous asphalt, or concrete) which allow stormwater percolation into the road structure, storage in an underground vault, and disposal either into surface waters (where conditions allow), or through infiltration into the surrounding soils. Both types of pavements provide good treatment of the percolating stormwater (Legret *et al.*, 1996; Bond *et al.*, 1999). Recent investigations of porous pavements focused on operational aspects, including surface clogging and maintenance (Raimbault *et al.*, 1999). Some concerns were expressed that widespread stormwater infiltration would elevate groundwater tables in urban areas and thereby increase groundwater infiltration into (leaky) sanitary sewers, with concomitant high inflows of ballast waters to wastewater treatment plants (Weiss and Brombach, 2001). Such concerns emphasise the need for integrated analysis and solutions when managing urban waters.

Water quality inlets. These structures were originally developed as small three-chamber storage tanks installed at inlets to the sewer system. They provide some stormwater treatment by sedimentation and skimming of floatables and oil, and are well suited for parking lots, and commercial or industrial land. The original designs suffered from the washout of deposited materials during severe storms (Schueler, 1987). Such problems should be corrected in newer oil/grit separators, which function similarly as water quality inlets. In Ontario, these devices are designed to provide a permanent storage of 15 m^3/impervious ha. While many of these designs indicate good potential for removing coarse solids (sand) and containing free oil spills (MOEE, 1994), their actual field performance is poorly known and further obscured by conflicting data from independent tests and those conducted or sponsored by equipment manufacturers. French experience with these systems indicates very low effectiveness, except for interception of accidental oil spills. Low pollutant removal rates and release of captured pollutants were reported (Aires and Tabuchi, 1995; Bardin *et al.*, 2001b).

Filters. Stormwater sand filters were introduced in the USA with good success (Urbonas, 1994). They are effective in removing pollutants, but to maintain their effectiveness, they may have to be back-washed regularly and the risk of clogging should be reduced by stormwater pre-treatment (Schueler, 1987). Simpler maintenance is achieved by breaking up (i.e. by raking) the surface layer that may get clogged by the formation of a biofilm. Good designs may serve up to 5 ha, use a sand layer of 0.5 m, operate with a hydraulic head of 0.6–1.0 m (higher heads compact sand), are equipped with a collector of the filtrate and an overflow/bypass structure (Urbonas, 1999). Biofilters (i.e. with a coarse medium with biofilm on granular surfaces) were also tested and show good promise for removal of dissolved heavy metals (Lau *et al.*, 2000; Mothersill *et al.*, 2000).

Community-level BMPs

These BMPs include infiltration facilities, stormwater ponds, constructed wetlands, extended detention basins, and multiple systems. Further details follow.

Community infiltration facilities. These facilities comprise infiltration trenches and basins of somewhat larger scales than those provided at the site level. Trenches are generally designed for contributing areas of less than 2 ha, and draw-down times of 24–48 hours. Infiltration basins were recommended (in Ontario) for contributing areas up to 5 ha, and soils with percolation rates > 60 mm/h (MOEE, 1994). Other concerns and design considerations are similar to those listed earlier under the site-level infiltration facilities.

Stormwater management ponds. Stormwater ponds are used widely in Australia, Canada, Northern Europe and the USA to provide various types of controls, including flow control (reduction of flow peaks), sedimentation (removing sand, and some silt and clay), and removal of dissolved pollutants by aquatic plants (Lawrence *et al.*, 1996; Van Buren *et al.*, 1997; Petterson, 1999). These BMPs require a fair amount of land, and also serve for aesthetic and recreational purposes. They are well suited for areas with community acceptance, contributing areas > 5 ha, low slopes, and the sites without shallow groundwater or bedrock. Wet ponds comprise a permanent pool, littoral zone (one third of the pond surface area), and dynamic storage, and are designed either for removal of total suspended solids (TSS), or TSS and phosphorus (P). For TSS removal, ponds are designed to detain a 2-yr, 24-h storm for 24–48 hours; for TSS and P removal, the ponds should provide a detention time of 14 days during the wettest month (i.e. the minimal period for P uptake by algae and for settling fine solids).

Pond components include an inlet (spreading the influent), sediment forebay (easily accessible for maintenance), outlet (preferably a perforated riser), outfall (protected by riprap) and an emergency overflow, which is usually designed for a 100-yr flood. The pond shape should be irregular and aesthetically pleasing (length to width > 3), 1–2.5 m deep (to reduce the risk of anoxia in bottom layers), and properly oriented with respect to prevailing winds (providing pond water turnover) and bird flights (often discouraging landing). There are some concerns about pond operation – safety, poorly designed or maintained facilities, heating up of pond water, and breeding of mosquitoes (Schueler, 1987). Regular pond maintenance is required, including removal of bottom sediments.

Ponds may accumulate large quantities of contaminated sediments, which have to be dealt with. Depending on catchment sources, such sediments may be polluted with heavy metals and persistent organic pollutants, including polycyclic aromatic hydrocarbons (PAHs). Heavy metals in deposited sediments occur in various species and may be released into the water column in response to changes in the water quality. The management of contaminated sediments from stormwater ponds deserves further attention. Coarse materials may be little polluted and can be reused in municipal operations, e.g. for land fill or winter road maintenance. Finer, more polluted sediments may require some processing and controlled disposal. Such processing may include mixing with mulch to reduce slumping, or a chemical treatment designed to remove metals (Anderson *et al*., 1998). Presence of contaminated sediments degrades the value of the pond habitat and may contribute to contaminant entry into the food chain (Bishop *et al*., 2000).

Constructed wetlands. Wetland BMPs provide stormwater detention and treatment by various processes, including filtration, infiltration, and biosorption, and remove both particulate and dissolved pollutants (Rochfort *et al*., 1997). Constructed wetlands are widely applicable, serving areas > 2 ha, with tight soils, low evapotranspiration and the presence of baseflow. Wetlands are designed similarly as wet ponds, but with a shallow depth (0.15–0.6 m deep) and storage sufficient to detain a 1-yr, 24-h storm for 24 hours. Typically, wetlands should occupy not more than 2% of the contributing catchment area. The difficulties associated with wetlands include thermal enhancement, seasonal variations in performance, poor performance during winter months, and complicated maintenance (MOEE, 1994).

Extended detention (dry) basins. Such basins are widely applicable and can provide stormwater settling in the areas where it is difficult to maintain wet facilities. They are designed to capture 85% of annual runoff, with a drawdown time of 24–48 hours. Outflow control is provided by a V-notch weir or a perforated riser, storage bottom and slide slopes are vegetated, and require a bypass for extreme events. Aesthetics of dry ponds with deposited sediment is questionable and there may be concerns about exposure of contaminated sediments (Schueler, 1987; Camp Dresser and McKee *et al*., 1993).

Multiple systems. In these systems, two or more BMPs may be stacked vertically or in a series, to increase the system performance or reliability, or to reduce the maintenance. Multiple systems are designed as combinations of the earlier discussed BMPs, and their examples include: a wet pond above a sand filter (to reduce filter clogging); an extended detention basin/sand filter, a detention basin/sand filter/wetland, wet pond/wetland, biofilter/wetland, biofilter/infiltration trench, and oil grit separator/wetland or biofilter.

Watershed-level measures

The watershed is a logical unit for water management planning. Watershed-wide planning (WWP) recognises the cumulative impacts, protects specific features and resources, supports land use decisions, improves source-control BMPs, and assists in BMP siting (i.e. local vs. regional facilities). The site resources to be protected in the watershed-wide stormwater management include wetlands (provide habitat, water storage and treatment), floodplains (provide flood conveyance, habitat, and recreation opportunities), riparian (forested) buffers (moderate stream temperatures and dissolved oxygen variation, protect stream banks and wildlife habitat), meadows (function as buffers), and soils (impact on water quality) (DDNREC and EMCBC, 1997). The stormwater management strategy is included in watershed plans, which are developed in a hierarchical manner, employ the ecosystem approach, and provide a basis for the development of more detailed plans. In general, plan goals must be attainable, endorsed by the public and economically responsible.

For practically all stormwater management measures, some guidance for their design, performance and maintenance is available in the literature. However, practical experience with these measures and cost data are often missing, or relate to different climates. The selection of BMPs is empirically based, generally starting with the application of source controls (policies) followed up by "structural" BMPs. The selection process starts with establishing the performance goals, listing solution alternatives, eliminating unfeasible measures, ranking the remaining measures with respect to benefit/cost ratios, and finally selecting the most effective combination of BMPs (Camp Dresser and McKee *et al*., 1993).

Influencing factors and trends

This chapter addresses some selected factors and trends, which influence the SWM practice in the surveyed countries. Perhaps the strongest trend and influencing factor is the continuing growth of urban population and the migration of people to urban areas. This trend is well documented in both developing and developed countries. For example, the City of Toronto is expected to almost double in the next 15 years and this fast growth in population will make the provision of water services, including urban drainage and protection of receiving waters, even more challenging. It is also recognised that this growing population is using increasing amounts of energy and various chemicals and materials, which lead to increased emissions into the environment and impacts on the receiving waters. In spite of SWM application in these areas, further increases in flow volumes, and possibly sediment and chemical fluxes appear to be unavoidable.

The current development of SWM is strongly affected by regulations and legislation. It was noted that in all the countries surveyed, there are laws and regulations, which apply to the control of stormwater and its management (Clifforde, 2001; Mather, 2001). These exist in various forms, ranging from general, broad-sweeping laws for the protection of the aquatic environment or ecosystems to laws or regulations specifically addressing stormwater (Roman, 2001). In the first category, one could name, e.g. the Canada Fisheries Act, which prohibits discharge of deleterious substances to open waters, which are inhabited by fish. In a legal precedent, the deleterious effect was determined by a toxicity bioassay. An example of a specific legislation is the U.S. Clean Water Act, implemented through the National Pollutant Discharge Elimination Program, which requires municipalities to apply for stormwater discharge permits. This application involves monitoring stormwater discharges for specific pollutants and a specified number of discharges, and where needed, a proposal of corrective measures (Torno, 1994). In other countries, the scope of stormwater regulations is more or less limited to water quantity issues, dealing mostly with peak runoff flow rates and their implications for flooding.

Another influencing factor is the risk of climate change caused by emissions of greenhouse gases. Climate change is viewed differently in various countries and by various professionals. While the increase in atmospheric concentrations of CO_2 is well documented, specific impacts on climatic factors are difficult to distinguish from their natural variability. Under such circumstances, many countries are adopting a precautionary approach by accepting the estimates of climate changes produced by global circulation models and assessing their potential impacts on design practice (Haikio, 2001). It should be recognised that the concrete storm sewers built today are likely to stay in service for the next 100 years and may be subject to different climatic conditions than currently assumed. With respect to SWM, several types of potential impacts of climate change can be envisaged and would result from changes in precipitation and air temperatures. Increasing precipitation and incidence of extreme events may increase runoff/streamflow discharges and lead to flooding. Reduced precipitation would affect wetlands and similar BMPs used in SWM. Changes in air temperatures are expected to lead to higher sea levels (with concomitant drainage difficulties in coastal areas), changes in snowmelt and streamflow in cold climate countries, and overall changes among the individual components of the hydrological cycle. SWM can play an important role in coping with these changes, as demonstrated in Japan for coping with increasing rainfall intensities by enhanced storage (Asada *et al*., 1999).

Three trends were identified in the national report: minimising the inflow of stormwater into sewers, growing participation of stormwater utilities, and a move towards adaptive water management. The overall trend in addressing stormwater issues in urban areas is towards practising SWM and minimising stormwater inflow into sewers, regardless of the sewer system used. Currently in Europe, this process is driven by the EU legislation and standards, with respect to both the EU members as well as the countries aspiring to join the union. This is a very ambitious and costly program, which requires all countries, regardless of their current level of development of water management (including SWM), to reach a common plateau in about 10 years. In France (Chocat, 2001), the cost of such an endeavour with respect to stormwater was estimated at 90 billion French francs (about 12 billion $U.S.). Thus, significant progress in SWM can be expected in EU countries in the next 10–15 years (the longer periods apply to full compliance of the EU candidates). Elsewhere in the world, SWM is driven by other factors, including flood management (Ha and Lee, 2001; Inoue *et al.*, 2001; Yew, 2001; e.g. in Hong-Kong SAR, China, Japan and Korea), and general goals of environmental protection (Markowitz, 2001; Roman, 2001).

There is an ongoing change in the ownership and operation of SWM systems. While traditionally the drainage systems were publicly owned and operated, there is trend towards other modes of ownership and operation, involving the private sector. Towards this end, stormwater utility companies (both public and private) are being set up and these then provide SWM services. Typically, these stormwater utilities operate within larger water companies, which can provide integrated services to urban populations.

Specific designs of SWM are covered by manuals with various levels of detail developed in most countries. These manuals deal with the overall SWM philosophy and the design of individual BMP measures. They are typically developed for local conditions and reflect the local climate, regulatory environment, economic conditions, public expectations with respect to SWM, cultural values, and engineering practices. Description of some basic processes (e.g. flow routing) are of course generic and can be adopted from the existing documents or textbooks. In most countries, strict adherence to these manuals or guides is not required and this leaves some room for the designer's creativity. Furthermore, it is now more and more recognised that some SWM BMP trains are complex measures, whose benefits with respect to aquatic ecosystems may be predicted with significant uncertainties. Under such circumstances, the adaptive-learning (rather than prescriptive) approach to stormwater management is preferred and consists of designing the "best" SWM system with the current level of knowledge and the available data, and allowing for further system improvements after its implementation and collection of actual performance data (Phillips *et al.*, 1999).

Economic considerations and financing

The evolution of stormwater management as a specific service for the benefits of the urban population and the environment in general led to some changes in the SWM economy and financing. Conventional systems used to comprise sewer networks only and those were publicly owned and operated. Modern SWM systems include many more elements, including various BMPs (ponds, wetlands, treatment facilities) and create totally different requirements with respect to their operation, economy and financing. Drainage systems with SWM often require lower initial investments and provide a higher level of service (i.e. not just drainage, but also water quality improvement) than the conventional systems. It is further recognised that SWM contributes significantly to the local economy, by maintaining or improving beneficial uses of receiving waters, reducing harmful impacts and associated damages (particularly flooding), and enhancing real estate values in well-designed areas. Also, the introduction of SWM led to the development of a new segment of the environmental technology industry, focusing on such products as stormwater filters, gross pollutant traps (particularly common in Australia and UK), and oil and grit separators. Some of these devices require regular servicing (e.g. removal of captured oil and sediment), and such services are now offered by newly formed private companies.

The sustainable operation of SWM systems requires sound financing for both the initial implementation and for continuous maintenance. In new areas, SWM financing is relatively easy – through lot levies and similar development fees. In the existing areas, the financing of retrofitted SWM is much more difficult and this is a major reason why the progress in SWM in older areas with sound (but possibly outdated) infrastructures is rather slow. The willingness to pay principle is a promising approach in this regard (Novotny *et al.*, 2001). SWM measures also require the financing of operating and maintenance costs. The old way of financing drainage services from the general municipal tax revenue still exists in some countries, but other models are being developed as well. The financing from general revenue suffers from the fact that as SWM systems age, they require more maintenance and resources, which may not be available in a tough competition with other water services, including water supply and wastewater management. Consequently, more and more countries (or cities) are switching to a separate financing of drainage and SWM by promoting the user pay principle and collecting drainage fees. These fees reflect the user's generation of runoff, which is considered to be proportional to the impervious area directly occupied by the user. To encourage SWM and reduce inputs to drainage systems, credits are given for any on-site BMPs and reductions in runoff discharge into the drainage system. The early experience with these charges in North America (USA, Canada) and Europe (Germany) is generally favourable.

Research and development

Stormwater management is undergoing rapid development, as demonstrated at many conferences on this subject and in journal publications. The analysis of national reports on SWM solicited by the IWA survey indicated that research and development needs in individual countries varied depending on the level of SWM development. Thus, in some cases, the main research needs concern traditional urban hydrology and drainage/flood protection issues, including rainfall statistics and the development of design rainfalls. Where requirements on urban drainage include water quality considerations, the research interests also cover the characteristics of stormwater (particularly highway runoff) and their impacts on the water quality in receiving waters. At the highest level of development, there is a strong interest in the methods and techniques for mitigation of stormwater impacts on the environment and ecosystems (Matos, 2001). Such research calls address best management practices in various climates (Argue, 1995; Thorolfsson, 2001), sustainability of urban drainage systems, and techniques and strategies for their catchment-wide planning, design and implementation. Samples of research problems currently studied are given below.

With respect to BMPs, there is a continuing interest in elucidating their long-term performance in mitigation of urban impacts on receiving waters and their aquatic ecosystems. While much has been published about short-term removals of various pollutants by BMPs, the information on long-term performance and its sustainability by preventive and corrective maintenance is rather limited. In the ongoing research, such issues are investigated for porous pavements (pollutant removal, longevity, maintenance), infiltration facilities (pollutant migration into soils, mobility of metals in infiltrating stormwater, risk of groundwater pollution by chemicals and bacteria), swales (identification of treatment processes and their contributions towards stormwater treatment, including settling and filtration), street sweeping (the effectiveness of modern equipment in the collection of fine particles, economic efficiency of pollutant removal by street sweeping vs. other BMPs), and stormwater ponds (layout and size parameter effects on pollutant removals). A database on BMP performance should help establish their important design parameters and elucidate the parameter effects on the BMP performance (Clary *et al.*, 2001).

Research continues on measuring the BMP efficiency in the protection of receiving waters, by such methods as toxicity measurements and the assessment of benthic communities (Rochfort *et al.*, 2000). These methods should remove some limitations of the strictly chemically based methods, which do not address the issues of chemical speciation or interaction, and the interpretation of the chemistry data with respect to the receiving water ecosystems. Research on the sustainability of urban drainage systems is in its infancy. So far, broadly accepted sustainability criteria, which would allow measurement of the sustainability of individual projects, have not been established. Some research has been conducted with respect to the methods for catchment protection planning, the selection of BMPs in response to the catchment planning needs, and implementation of SWM. More research is needed on the interaction of technical and social issues, including social marketing of SWM and the public education and participation in this process.

Emerging issues in SWM include introductions of new chemicals posing water quality threats, continuing accumulation of contaminated sediments in BMPs and receiving waters with the associated cumulative impacts, and concerns about potential climate change, expressed in several national reports (precipitation changes; higher air temperatures, rising sea, different water quality process rates). Among the engineering problems, challenges of ageing infrastructures and their deteriorating performance are recognised in some countries and call for new investments in infrastructure rehabilitation (Arsov, 2001). Future trends include continuing research on SWM issues, knowledge sharing, and a greater participation of the private sector in the operation and ownership of drainage systems.

Conclusions

The issues of stormwater runoff in urban areas attract a great deal of attention in all the countries surveyed, for a variety of reasons, including concerns about stormwater impacts on flooding and water quality, and the sustainability of receiving water ecosystems. These driving forces reflect local conditions with respect to the climate, economic development, the level of environmental protection practice (including the associated infrastructures), institutional arrangements and public awareness. All national reports share a common vision with respect to the basic philosophy of coping with stormwater problems – by means of a holistically based management, rather than continuing the traditional expansion (or neglect) of urban drainage systems. This vision is reflected in a number of specific findings, needs or proposed actions, including the following:

- Developing drainage systems in an environmentally sensitive and sustainable way, by preserving water balance in the affected areas and preventing the entry of sediment and pollutants into stormwater as much as possible (note, however, that the implementation of this approach in older areas is falling behind).
- Emphasising source controls in stormwater management, by reducing or even preventing runoff generation and pollution as close to sources as possible. In existing areas, this principle is applied during their redevelopment by disconnecting the runoff-contributing areas from sewers.
- Urban drainage infrastructures are significantly changing from the older systems with pipes only, to new, more environmentally friendly systems (green infrastructures) encompassing attractively landscaped ponds, wetlands, infiltration sites and swales. There is an urgent need for drainage infrastructure development, maintenance and rehabilitation, with adequate financing, best provided through drainage fees rather than general taxation.

- Operation of new stormwater management systems requires dedicated agencies, preferably operating within the integrated water management authorities. In this system, various mixes of public and private sector partnership are promoted, to find the best combination fitting the local conditions. Furthermore, these agencies should be locally based and responsible to their local clientele, whose interests they have to serve.
- To ensure further progress in stormwater management, there is a great need for research and development, and knowledge sharing. IWA is well positioned to play a significant role in this respect, particularly through its Specialist Group on Urban Drainage, which is operated jointly with IAHR under the name of the Joint Committee on Urban Drainage.
- Finally, urban drainage touches the lives of practically all urban dwellers. It is therefore important to keep the public awareness, education and participation in the forefront of all stormwater management activities, recognising that the success of stormwater management depends on public support and participation.

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References

Aires, N. and Tabuchi, J.P. (1995). Les séparateurs à hydrocarbures et la dépollution des eaux pluviales. *TSM-L'eau Spécial eau pluviale*, **11**, 862–863 (in French).

American Society of Civil Engineers (ASCE) (1998). Urban runoff quality management. *WEF Manual of Practice No. 23, ASCE Manual and Report on Engineering Practice No. 87, ASCE*, Reston, VA, USA.

Andersen, T. and Schilling, W. (2001). Stormwater source controls in an urban rehabilitation project in downtown Oslo, Norway. In: *Proceedings of the 4th international conference on Innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 349–356.

Anderson, B.C., Brown, A.T.F., Watt, W.E. and Marsalek, J. (1998). Biological leaching of trace metals from stormwater sediments: influential variables and continuous reactor operation. *Wat. Sci. Tech.*, **38**(10), 73–81.

Appan, A. (1999). A dual-mode system for harnessing roofwater for non-potable uses. *Urban water*, **1**(4), 307–316.

Argue, J.R. (1995). Towards a universal stormwater management practice for arid zone residential developments. *Wat. Sci. Tech.*, **32**(1), 1–6.

Arsov, R. (2001). *National report on stormwater management in Bulgaria*. A report submitted to IWA, London.

Asada, K., Kawaguchi, T. and Zhang, S.P. (1999). Evaluations of impacts of global warming on urban drainage systems. In: *Joliffe I.B. and Ball J. (eds.), Proceedings of the 8th International Conference on Urban Storm Drainage*, Sydney, Australia, Aug. 30–Sept. 3, 1999, pp. 373–378.

Azzout, Y., Barraud, S., Cres, F.N. and Alfakih, E. (1994). *Techniques alternatives en assainissement pluvial. Choix, conception, réalisation et entretien*. Tec. et Doc., Lavoisier, Paris (in French).

Bacon, M. (1997). Integrated planning for sustainable urban water resources. *Sustaining urban water resources in the 21st century, Engineering Foundation Conference*, Malmo (Sweden), Vol. 1, pp. 1–2.

Balades, J.D. and Petitnicolas, F. (2001). Strategies of wet weather pollution control at source – a technical and financial approach. In: *Proceedings of the 4th international conference on innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 367–373 (in French).

Bardin, J.P., Barraud, S. and Dechesne, M. (2001a). Elaboration of performance indicators for stormwater infiltration strategies. In: *Proceedings of the 4th international conference on innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 1003–1006 (in French).

Bardin, J.P., Gautier, A., Barraud, S. and Chocat, B. (2001b). The purification performance of infiltration basins fitted with pre-treatment facilities: a case study. *Wat. Sci. Tech.*, **43**(5), 119–128.

Barraud, S., Azzout, Y., Cres, F.N. and Chocat, B. (1999). Selection aid of alternative techniques in urban storm drainage – proposition of an expert system. *Wat. Sci. Tech.*, **39**(4), 241–248.

Bertrand-Krajewski, J.L., Barraud, S. and Chocat, B. (2000). Need for improved methodologies and measurements for sustainable management of urban water systems. *Environmental Impact Assessment Review*, **20**, 323–331.

Bishop, C.A., Struger, J., Shirose, L.J., Dunn, L. and Campbell, G.D. (2000). Contamination and wildlife communities in stormwater detention ponds in Guelph and the Greater Toronto Area, Ontario, 1997 and 1998. Part II – contamination and biological effects of contamination. *Water Qual. Res. J. Canada*, **35**(3), 437–474.

Bond, P.C., Pratt, C.J. and Newman, A.P. (1999). A review of stormwater quantity and quality performance of permeable pavements in the UK. *8th ICUSD*, Sydney (Australia), Aug. 30–Sept. 3, pp. 248–255.

Camp Dresser McKee, Larry Walker & Associates, Uribe & Associates and Resource Planning Associates (1993). *California stormwater best management practice handbooks*.

Chocat, B. (2001). *National report on stormwater management in France*. A report submitted to IWA, London.

Chocat, B., Barraud, S. and Alfakih, E. (2001a). Development of BMPs: Recent progress in France and other countries of western Europe. In: *Linking stormwater BMP designs and performance to receiving water impacts mitigation*. UEF conference, Snowmass – Colorado (USA) 19–24 August, Proceedings to be published.

Chocat, B., Krebs, P., Marsalek, J., Rauch, W. and Schilling, W. (2001b). Urban drainage redefined: from stormwater removal to integrated management. *Wat. Sci. Tech.*, **43**(5), 61–68.

Clary, J., Urbonas, B., Jones, J., Strecker, E., Quigley, M. and O'Brien, J. (2001). Developing and evaluating a stormwater BMP effectiveness database. *Wat. Sci. Tech.* **45**(7), 65–73.

Clifforde, I. (2001). *National report on stormwater management in the United Kingdom*. A report submitted to IWA, London.

Davis, C. (2001). *National report on stormwater management in Australia*. A report submitted to IWA, London.

Delaware Department of Natural Resources and Environmental Control (DDNREC) and the Environmental Management Center of the Brandywine Conservancy (EMCBC) (1997). *Conservation design for stormwater management*. Available from DDNREC, Dover, Delaware, USA.

Ellis, J.B. (1995). Integrated approaches for achieving sustainable development of urban storm drainage. *Wat. Sci. Tech.*, **32**(1), 1–6.

Fewkes, A. (1999). Modeling the performance of rainwater collection systems: towards a generalized approach. *Urban water*, **1**(4), 323–333.

Field, R., Borst, M., O'Connor, T., Stinson, M.K., Fan, C.Y., Perdek, J.M. and Sullivan, D. (1998). Urban wet-weather flow management: research directions. *ASCEE, Jour. of Wat. Res. Plan. and Manag.*, May/June, 168–180.

Fujita, S. (1998). Towards "zero emissions" in urban drainage works. *Novatech98 (IAHR/IAWQ)*, vol 2, pp. 209–215.

Geiger, W.F. and Dreiseitl, H. (1995). *Neue Wege fuer das Regenwasser* (in German; A new way for stormwater disposal). R. Oldenbourg Verlag GmbH, Munich, Germany.

Geldof, G. (2001). Stormwater source control and public acceptance. In: *Advances in urban stormwater and agricultural runoff source controls*, Marsalek, J., Watt, W.E., Zeman, E. and Sieker, H. (eds) (in press), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 295–304.

Ha, S.-R. and Lee, H.-D. (2001). *Stormwater management with respect to combined sewer outflows in Korea*. A national report submitted to IWA, London, UK.

Haikio, E. (2001). *National report on Finish stormwater management*. A report submitted to IWA, London, UK.

Hermann, T. and Schmida, U. (1999). Rainwater utilisation in Germany: efficiency, dimensioning, hydraulic and environmental aspects. *Urban water*, **1**(4), 307–316.

Inoue, Y., Matsubara, M. and Nakamura, E. (2001). *Overview of stormwater management in Japan*. A national report submitted to IWA, London, UK.

Lau, Y.L., Marsalek, J. and Rochfort, Q. (2000). Use of a biofilter for treatment of heavy metals in highway runoff. *Water Qual. Res. J. Canada*, **35**(3), 563–580.

Lawrence, A.I., Marsalek, J., Ellis, B.J. and Urbonas, B. (1996). Stormwater detention and BMPs. *J. Hydraulic Res.*, **34**(6), 799–814.

Legret, M., Colandini, V. and Le Marc, C. (1996). Effects of a porous pavement with a reservoir structure on the quality of runoff water and soil. *Sci. Tot. Environment*, **189/190**, 335–340.

Lucino, A. (2001). *National report on stormwater management in Spain*. A report submitted to IWA, London, UK.

Malmquist, P.-A. and Bennerstedt, K. (2001). *Stormwater management in Sweden*. A national report submitted to IWA, London, UK.

Markowitz, D.V. (2001). *Stormwater management in the United States*. A national report submitted to IWA, London, UK.

Marsalek, J. (1998). Challenges in urban drainage. In: *Hydroinformatics tools for planning, design, operation and rehabilitation of sewer systems*, Marsalek, J., Maksimovic, C., Zeman, E. and Price, R. (eds), NATO ASI Series, 2. Environment – vol 44, Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 1–23.

Mather, A. (2001). *National report on stormwater management in South Africa*. A report submitted to IWA, London, UK.

Matos, R. (2001). *National report on stormwater management in Portugal*. A report submitted to IWA, London, UK.

McKissock, G., D'Arcy, B. and Jefferies, C. (2001). Sustainable Urban Drainage: A Case Study. In: *Proceedings of the 4th international conference on Innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 333–340.

Mikkelsen, P.S., Adeler, O.F. Albrechtsen, H.J. and Henze, M. (1999). Collected rainfall as a water source in Danish households – what is the potential and what are the costs. *Wat. Sci. Tech.*, **39**(5), 49–56.

Ministry of Environment and Energy (MOEE). (1994). *Stormwater management practices planning and design manual*. Ontario Ministry of the Environment, Toronto.

Mok, K.K.K. (2001). *Stormwater management in Hong Kong Special Administrative Region, China*. A report submitted to IWA, London, UK.

Mothersill, C.L., Anderson, B.C., Watt, W.E. and Marsalek, J. (2000). Biological filtration of stormwater: field operations and maintenance experiences. *Water Qual. Res. J. Canada*, **35**(3), 541–562.

Neittzke, S. (1999). *Alternative techniques around the world – International literature review and case study*. Report INSAVALOR, Lyon, (France).

Novotny, V., Clark, D., Griffin, R. and Bartosova, A. (2001). Balancing flood control and ecological preservation/restoration of urban watersheds. In: *Advances in urban stormwater and agricultural runoff source controls*, Marsalek, J., Watt, W.E., Zeman, E. and Sieker, H. (eds) (in press), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 39–56.

Petterson, T.J.R. (1999). *Stormwater ponds for pollution reduction*. PhD thesis, Chalmers University of Technology, Goteborg, Sweden.

Phillips, B.C., Lawrence, A.I. and Boon, B. (1999). City of Clarence (Tasmania) stormwater management strategy. In: *Proceedings of the 8th International Conference on Urban Storm Drainage*, Joliffe, I.B. and Ball, J. (eds), Sydney, Australia, Aug. 30–Sept. 3, pp. 801–808.

Raimbault, G., Nadji, D. and Gauthier, C. (1999). Stormwater infiltration and porous material clogging. In: *Proceedings of the 8th International Conference on Urban Storm Drainage*, Joliffe, I.B. and Ball, J. (eds), Sydney, Australia, Aug. 30–Sept. 3, pp. 1016–1024.

Rochfort, Q.J., Anderson, B.C., Crowder, A.A., Marsalek, J. and Watt, W.E. (1997). Sub-surface flow constructed wetlands for stormwater quality enhancement. *Water Qual. Res. J. of Canada* **32**(1), 101–117.

Rochfort, Q., Grapentine, L., Marsalek, J., Brownlee, B., Reynoldson, T., Thompson, S., Milani, D. and Logan, C. (2000). Using benthic assessment techniques to determine combined sewer overflow and stormwater impacts in the aquatic ecosystem. *Water Qual. Res. J. of Canada* **35**(3), 365–397.

Roman, M. (2001). *National report on stormwater management in Poland*. A report submitted to IWA, London, UK.

Schmitt, T.G. (2001). *National report on stormwater management in Germany*. A report submitted to IWA, London, UK.

Schueler, T.R. (1987). *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*. Washington Metropolitan Water Resources Planning Board, Washington, DC.

Smith, P. (2001). The role of education in stormwater management. In: *Proceedings of the 4th international conference on Innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 443–450.

Thorolfsson, S.T. (2001). *Stormwater management in Norway*. A national report submitted to IWA, London, UK.

Torno, H.C. (ed.). (1994). Stormwater NPDES related monitoring needs. *Proceedings of an Engineering Foundation Conference*, Crested Butte, CO, USA, published by ASCE, New York, USA.

Urbonas, B. (1994). Assessment of stormwater BMPs and their technology. *Wat. Sci. Tech.*, **29**(1–2), 347–353.

Urbonas, B.R. (1999). Design of a sand filter for stormwater quality enhancement. *Water Env. Res.*, **71**(1), 102–113.

U.S. Environmental Protection Agency (EPA). (1983). *Results of the Nationwide Urban Runoff Program Volume I – Final Report*. Water Planning Division, U.S. EPA, Washington, DC.

Van Buren, M.A., Watt, W.E. and Marsalek, J. (1997). Removal of selected urban stormwater constituents by an on-stream pond. *J. of Env. Planning and Management*, **40**(1), 5–18.

Weiss, G. and Brombach, H. (2001). Water pathways in urban hydrology: results of a field study. In: *Proceedings of the 4th international conference on Innovative technologies in urban storm drainage*, Lyon, France, June 25–26, pp. 307–314.

Yew, K. (2001). *National report on stormwater management in Malaysia*. A report submitted to IWA, London.

Zabkova, I., Macek, L. and Svec, L. (2001). *Storm water management – Czech Republic National Report*. A report submitted to IWA, London.